HF Surface Wave Radar Operation in Adverse Conditions

Anthony M. Ponsford, Reza M. Dizaji and Richard McKerracher
Raytheon Canada Limited, Waterloo, ON N2J 4K6 Canada
E-mail: tony_ponsford@raytheon.com, reza_dizaji@raytheon.com, rick_mckerracher@raytheon.com

Abstract—**For the past 12 years the Canadian Department of National Defence and Raytheon Canada Limited have collaborated on a cost-shared programme to develop an Integrated Maritime Surveillance (IMS) system based on HF Surface Wave Radar (HFSWR).**

The primary objective behind the programme was to demonstrate the capability of HFSWR to continuously detect and track surface targets (ships and icebergs) as well as airborne targets, at all altitudes, to ranges in excess of 200 nautical miles, reliably and consistently in real time and in all weathers. A secondary objective was to demonstrate the concept of IMS, involving the fusing of data from HFSWR radars and other sensors.

This paper reviews techniques and methods used in the processing of HFSWR data to ensure that performance is maintained, even under adverse operating conditions.

I. INTRODUCTION

The United Nations' "Law of the Sea" grants maritime nations sovereign rights over an area of ocean known as the Exclusive Economic Zone (EEZ) that extends 200 nautical miles from shore. In return, these nations are required to establish and maintain administration, law enforcement and environmental protection over this area. This requires that ship and aircraft activity within their EEZ be monitored. Ships can be monitored intermittently and at great cost by air patrols, sea patrols or possibly satellites, but HFSWR is the only sensor that offers the capability of inexpensive surveillance of a large area, with the ability to track targets continuously and in all weathers. HFSWR provides track information and can classify contacts in terms of size (i.e. radar cross section), track history, heading and speed. Moreover, by providing current locations and tracks of specific contacts, HFSWR can improve the effectiveness of other reconnaissance assets, such as patrol aircraft, in providing positive identification.

An IMS system uses HFSWR to provide a background layer of current and past activity, onto which other data from complementary sensors and resources are mapped. HFSWR is used to maintain the validity of tracks of targets that have been identified by other means, as well as to cue other sensors and assets such as patrol aircraft.

Extensive testing of the HF Radar system has been undertaken over the past three years [1, 2], and it has been shown that the system performance during daylight hours is satisfactory, but that night time performance can be degraded by high external interference, range-wrapped ionospheric clutter and external noise. In addition, high clutter levels experienced during periods of high sea states can adversely affect detection of small targets.

This paper introduces some key factors that can improve the performance of HFSWR, and demonstrates the effectiveness of mitigation techniques. These techniques help ensure optimal performance of an HFSWR system, even in extremely adverse conditions.

II. THE HFSWR SYSTEM

Two SWR-503 HFSWRs, developed by Raytheon Canada Limited, have been in operation on Canada's East Coast since 1999. Key operational parameters are listed in Table I, below.

The system uses a phase-code sequence on transmit, which permits operation at a high Pulse Rate Frequency (PRF), while suppressing range sidelobes and "range-wrapped" ionospheric clutter. The radar uses "mismatched" phase-code sequences to allow the system to suppress strong co-channel interference signals.

While the bandwidth gives a range resolution of 7.5 km, over range-sampling produces an accuracy of 0.3 km. Beam widths are approximately 8°, and target angles of arrival estimates are determined with a detection error of less than 1.0° over the radar coverage area of ±60° from boresight.

The 1.6 kW (average) transmitter power ensures ocean clutter limitation to greater than 350 km range during the day, but at night the system is typically externally noise-limited from approximately 150 km.

TABLE I
PARAMETERS OF THE HFSWR AT CAPE RACE, NEWFOUNDLAND

Frequency	3-5 MHz
Transmit antenna:	7-element log-periodic monopole. Gain ~8 dBi
Receive antenna:	Linear array of 16 monopole doublets. 33m spacing.
Transmit power:	16 kW peak, 1.6kW av.
Waveform:	Sequence of phase codes.
PRF:	250 Hz
Pulse bandwidth:	20 kHz
Sampling Rate:	100 kHz

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **14 APR 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **HF Surface Wave Radar Operation in Adverse Conditions**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Raytheon Canada Limited, Waterloo, ON N2J 4K6 Canada**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001798, Proceedings of the International Conference on Radar (RADAR 2003) Held in Adelaide, Australia on 3-5 September 2003., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**6**	

III. Target Detection

The performance of HFSWR is adversely affected by a number of environmental factors [3]. Digital signal processing techniques are used to mitigate these effects.

A target is detected by comparing the power in a given radar pixel relative to its neighbours. The radar pixel is bounded in azimuth, range and Doppler. A typical HFSWR may have 10 million pixels per dwell. In an ideal situation, a pixel contains a target return or spatially temporally white external noise. However, other unwanted signals may also be present. These unwanted signals fall into two distinct categories:

1) External Interference: where the unwanted signal is independent of the radar operation, e.g. co-channel interference and impulsive noise; these signals behave as additive noise.

2) Clutter: where the unwanted signal is a consequence of the radar's operation, e.g. ionospheric clutter, ocean clutter, range wrap clutter and meteor clutter. These signals behave as multiplicative noise.

Target detection generally degrades at night. This is because ionospheric conditions change with time of day and season. During daylight hours, ionospheric propagation between 3 and 7 MHz (i.e. short-wave) is extremely lossy due to D-layer absorption. At night, the D-layer disappears, leaving the way open for short-wave signals to propagate in from around the world. This also includes lightening noise that propagates via the ionosphere and hence increases the background noise level.

Not all the energy emitted by the radar propagates as a surface wave. Some energy is directed upwards, and may reflect from the ionosphere, either directly back to the radar, or indirectly by a second reflection of the ocean. This latter case may be viewed as multipath clutter, and given the geometry of the problem, these echoes usually appear as range wrap or "second-time-arounds."

The interaction of the electromagnetic wave with the ocean wave results in an ocean clutter spectrum that is typically the limiting factor in surface target detection. This clutter spectrum has been extensively modelled and is described in detail [4].

IV. Clutter Mitigation

Clutter is defined as unwanted echoes. These unwanted echoes are typically characterized as originating from a collection of spatially distributed scatterers, and do not have the characteristic thumbtack ambiguity function of a point target. For a HFSWR the dominant forms of clutter are ocean clutter and ionospheric clutter. Detection in these situations can be enhanced by distributing the clutter energy over a larger number of pixels, by either improving the range, Doppler, or azimuth resolution, or by exploiting the characteristic of the clutter signal to remove it.

The radar returns from the ocean surface have a complex structure. The sea surface is composed of waves of different wavelengths and amplitudes travelling in different directions. The resultant clutter is dominated by back-scatter from components of the sea spectrum which are resonant with the radar wavelength. Two dominant first-order peaks impair radar detection at their corresponding Doppler frequencies. However, the part of the ocean clutter that affects the performance of HFSWR in detecting low-speed ships is the continuum. The level of the ocean clutter at a given Doppler is influenced by the power of the wind, and its directionality with regard to the radar look direction,. This directionality of the spectra does not imply that the ocean clutter has a strong spatial correlation. In fact, it has a very poor spatial correlation. This can be exploited by using a sub-space processing technique to suppress the clutter and enhance target detection. A detailed description of the algorithm can be found in [5].

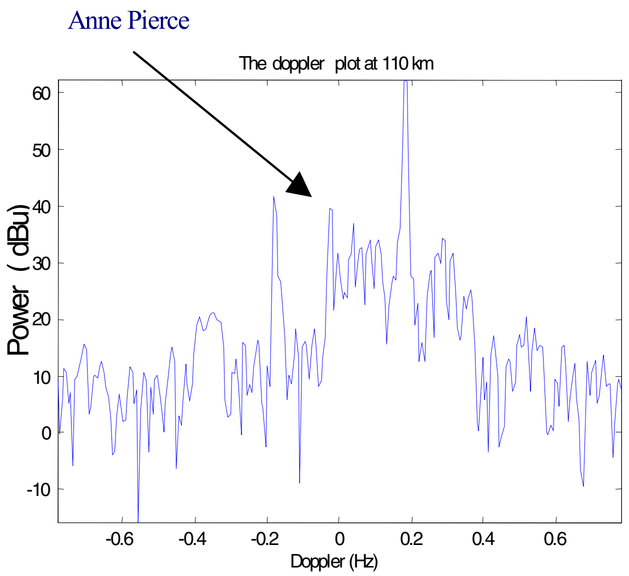

Fig. 1. Doppler Plot at the Range of the Target – Standard FFT Processing.

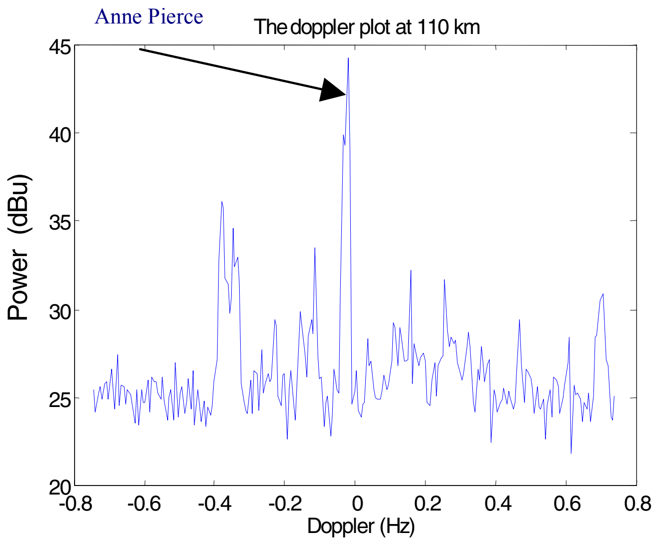

Fig. 2. Doppler Plot at the Range of the Target – Sub-Space Processing.

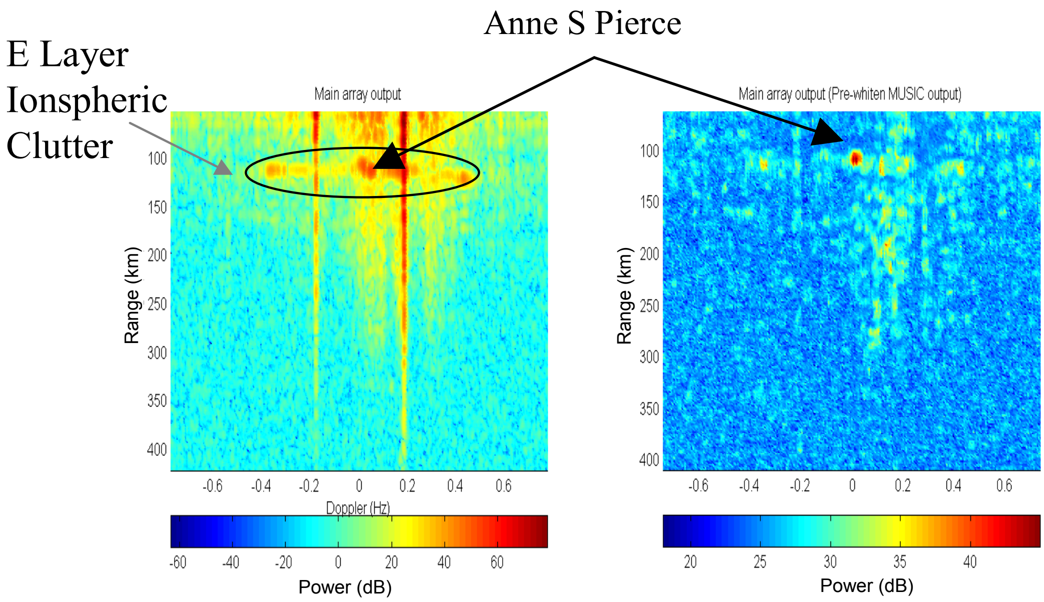

Fig. 3. Target Detection in Ionospheric Clutter.

The effectiveness of the algorithm is illustrated using data collected from a controlled test target - a 40m scallop boat. The trials were conducted during gale-force winds and seas of 3 to 4 metres. Fig. 1 plots the output of the FFT beamformed Doppler spectrum. It can be observed that a strong clutter continuum prevents the detection of this small target. Fig. 2 presents the data after sub-space processing. It can be observed that the ocean clutter has effectively been suppressed, including the first order, and that the target is now detectable with a 20 dB signal-to-clutter ratio.

Ionospheric clutter, on the other hand, exhibits spatial correlation. However, clutter suppression techniques have been shown to be effective in improving detection when the target's azimuth is removed from that of the ionospheric clutter. This is illustrated in Fig. 3, which plots the Range and Doppler spectrum at the target beam. The data was obtained from the same trial, but at a time when there were strong E-layer reflections, resulting in a broad Doppler band of clutter at 100 km. It can be observed that the subspace processing method has cancelled the clutter to reveal the target.

The third type of clutter is the result of skywave propagation that results in second- or higher-order range wrap and consequently results in the folding of echoes arriving from ranges beyond the maximum unambiguous range into the radar range. As illustrated in Fig. 4, phase coding of the transmitted pulse sequence is very effective in removing these unwanted signals.

The final clutter signal to be discussed is meteor clutter. This clutter is the result of radar reflections from the ionised trail. Meteor echoes as observed by an HF Radar are usually the result of line-of-sight propagation at a slant range of 100 to 250 nautical miles. The echo signature usually lasts for a few seconds, and appears as large peak at a specific range.

V. External Interference Mitigation

The HF band is highly congested with frequency allocations shared between many users. During the day, the occurrence of the D-layer prevents skywave propagation at these frequencies, and co-channel interference from local users in the band can be avoided by careful choice of

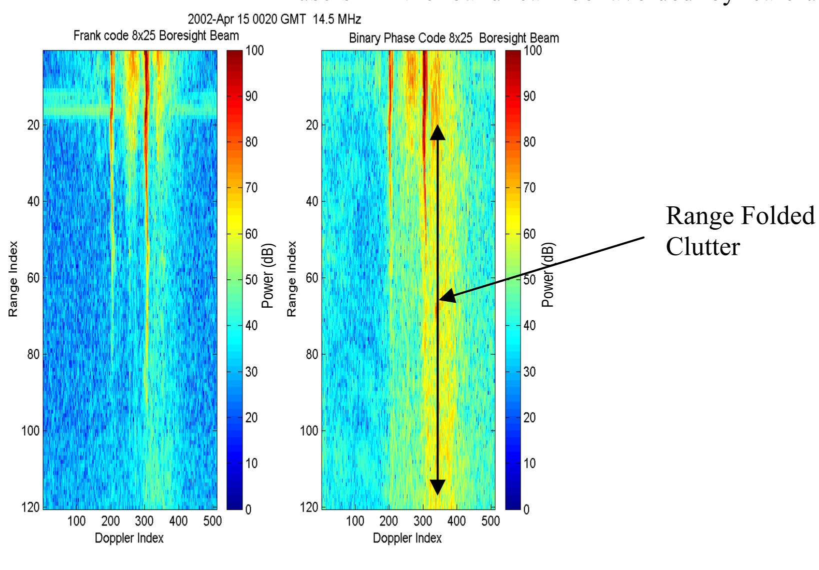

Fig. 4. Example of Range-Wrap Clutter Suppression using Quadrature Phase Coding. (a) Range Doppler Spectra processed using Frank Quadrature Phase Code (b) Data taken at approximately the same time using a binary phase code showing range-wrap clutter.

operating frequency. However, during the night, the ionosphere changes such that long-range skywave propagation is supported, and interference sources propagate into the area from around the world.

External interference is independent of the radar operation, and includes both co-channel interference and impulsive noise. Co-channel interference cancellation is achieved based on mismatched filtering to the radar transmitted codes. The matched filter response contains both the radar return and the interference, whilst the ancillary mismatched data contains only the interference. Subtraction leaves only the radar data. Details of the approach can be found in [6].

The effectiveness of the technique is illustrated in Fig. 5, which plots the beam outputs for the matched filter data (uncancelled beam) and the mismatched filter beam output.

Subtraction of one from the other leaves the clean External Interference Cancelled (EIC) beam output, from which the interference has been removed. The fourth plot is a Doppler profile taken at a range index of 40 before and after cancellation. It can be observed that the external interference has been suppressed by up to 20 dB and down to the external night-time noise level.

Impulsive noise is the result of local lightning discharges. These result in large spikes that have a short life, and in general only affect a few received pulses.

A simple and effective method to remove these spikes is to simply remove those pulses that exceed a given threshold level. This crude method is very effective but does result in a spreading of the Bragg energy that can potentially mask small targets. An alternative technique uses a predictive filter to both remove and reconstruct the original signal.

The approach is illustrated in Figure 6, which presents a plot of the amplitude of the time series (pulse index) of data. Impulsive noise (in this case a swept tone resulting from an ionospheric sounder) can be seen at pulse index 380.

The standard method for dealing with this is a straightforward blanking technique. This gives satisfactory results in most cases, but can result in a slight smearing of the Bragg energy. The alternative is to reconstruct the original signal using a Linear Prediction filter. The results from the two methods are compared in Fig. 7 using data collected from a HFSWR system operating at 14.5 MHz.

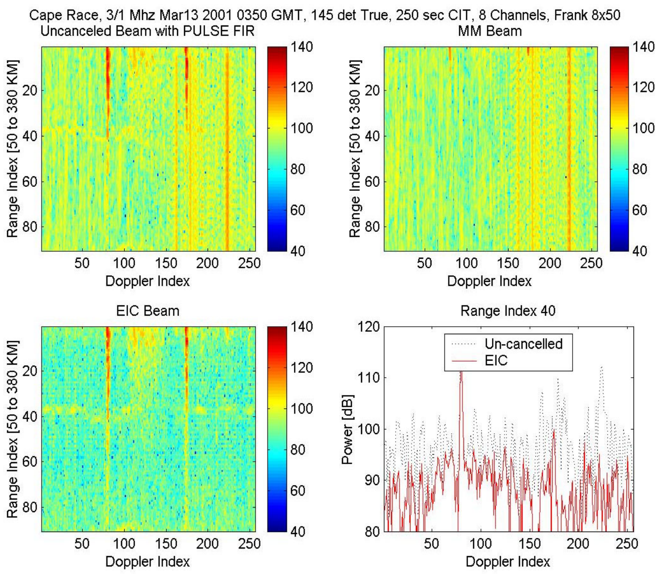

Fig. 5. External Interference Cancellation (EIC) Based on Matched/Mismatched Filtering: Data taken from Cape Race Radar Operating at 3.1 MHz at 0350z Mar 13, 2001.

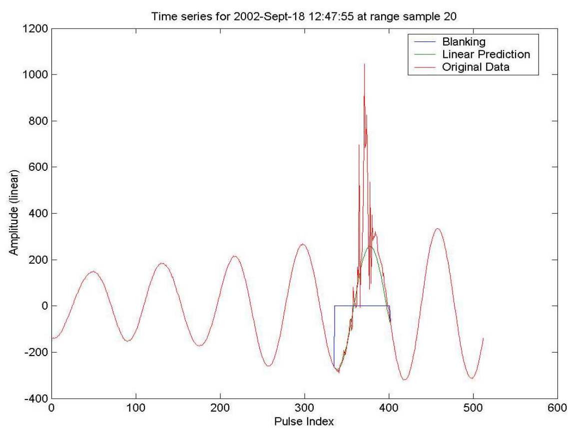

Fig. 6. Impulsive Noise Excision: Blanking and Linear Prediction.

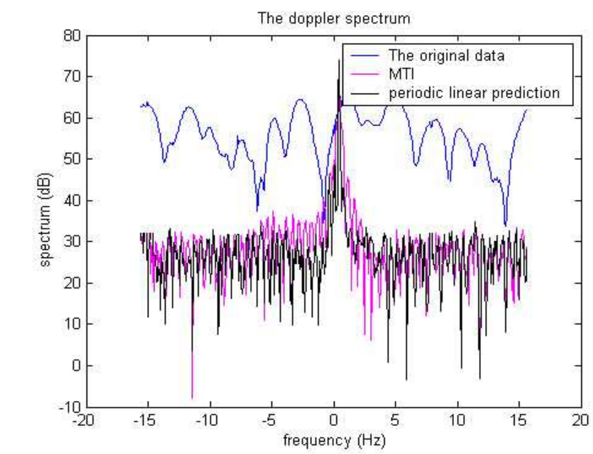

Fig. 7. Comparison of Impulsive Noise Excision Techniques.

VI. TRACKING

The next step in the process is to associate consecutive detections to form tracks. This can be a relatively easy process in low-density traffic areas but offers a significant challenge in dense target situations.

It is required that the radar tracks all vessels from first detection until they leave the coverage area or exceed their maximum detection range. This has to be accomplished with a minimum display of false tracks. Tracking will also improve the positional accuracy of the radar by smoothing the noise error. For an established track, track accuracy is typically better than 0.25 nm in range, 0.25 degree in azimuth.

The Tracker is described in detail in [7]. The tracker is a deferred-decision-based tracker that propagates multiple hypotheses at the report-to-track assignment stage (i.e. is it a true detection, a false detection, or a missed detection). These multiple track options are maintained over several update periods until a firm decision concerning the likelihood of a track can be established and competing tracks deleted. The report-to-track assignment is a multi-dimensional process incorporating target dynamic information (range, speed and azimuth) as well as rank information (target cross section). False tracks are minimized by using a multiple-stage assignment process, as shown in Table II.

TABLE II
TRACKER LOGIC

Potential Tracks (P):	single detection
Tentataive Tracks (T):	2 or more associated detections
Confirmed Tracks (C):	tracks with at least N associated detections, where N is user defined to meet false track rate
Deleted Tracks (D):	Tracks are coasted for a maximum on M consecutive misses prior to deletion.

VII. AN EXAMPLE OF MARITIME SURVEILLANCE PICTURE

This paper has shown that signal processing techniques can effectively remove unwanted interference and clutter from the radar data, allowing echoes from point targets to be cleanly extracted. Consecutive detections are then processed to produce tracks.

An example of typical track activity of the East Coast of Canada is presented in Figure 8. This data was extensively ground truthed using Maritime Patrol Aurora CP3 aircraft and a Fisheries aircraft equipped with Airborne Search Radar. A gale warning was in effect at the time of the trials, with winds Southeast 25-35 kts and seas of 3-4 meters.

The radar successfully tracked all reported targets and maintained a false alarm rate of better than 0.25 per hour.

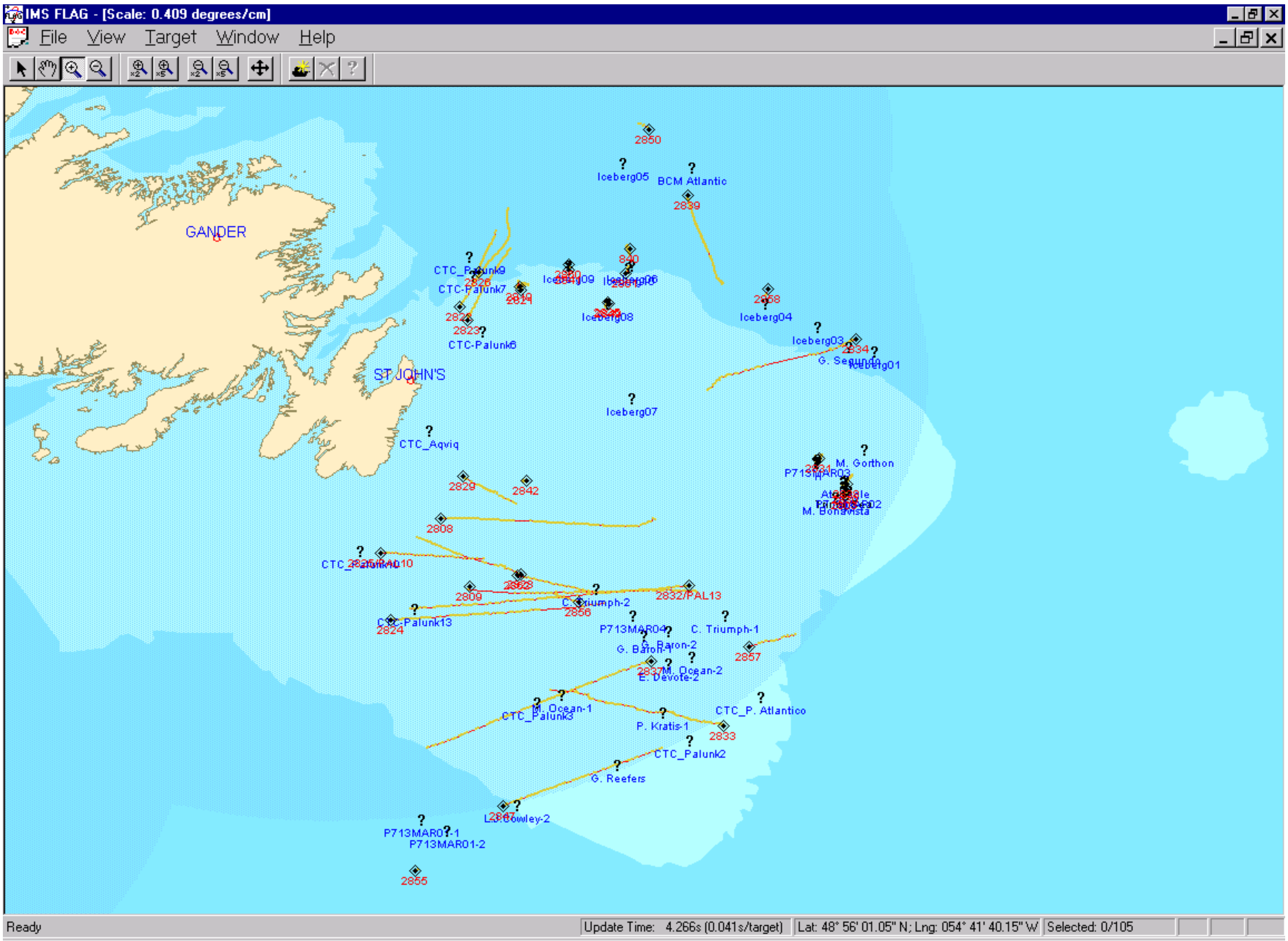

Fig. 8. Typical Radar Display, East Coast of Canada.

VIII. CONCLUSION

HFSWR has been evaluated as a key sensor in providing complete surveillance of surface and air activity within the Canadian EEZ. It has been shown that signal processing techniques can be applied to the radar data to overcome severe environmental impacts on radar detection performance. The HFSWR is a viable sensor, even though its performance is subject to time of day and seasonal variations, as well as sea state conditions and wind direction.

HF Radar has been shown to provide consistent and continuous real-time tracking of targets within the EEZ. When associated with detail obtained from other sources, a clear, unambiguous, picture of surface and air activity (at all altitudes) can be maintained.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Department of National Defence, Defence Research Development Canada (DRDC) and the Canadian Coast Guard for their continued support of the programme.

REFERENCES

[1] A.M. Ponsford, L. Sevgi, H.C. Chan, "An integrated maritime surveillance system based on high-frequency surface-wave radars. Pt 2, Operational status and system performance*," IEEE Antennas and Propagation Magazine,* vol. 43, no. 5, pp. 52-63, October 2001.

[2] A.M. Ponsford, "Surveillance of the 200 Nautical Mile Exclusive Economic Zone (EEZ) Using High Frequency Surface Wave Radar (HFSWR)," *Can. J. Rem. Sens.* vol. 27, no. 4, Special Issue on Ship Detection in Coastal Waters, pp. 354-360, August 2001.

[3] L. Sevgi, A.M. Ponsford, "Propagation and Interference Characteristic of High Frequency Surface Waves," *URSI, XXVIth General Assembly, F7: Wave Propagation and Remote Sensing,* August 13-21, 1999.

[4] S. Srivastava, J. Walsh, "An analysis of the second order Doppler return from the ocean surface," *IEEE J. Oceanic Engineering,* OE-10, pp. 443-445, 1985.

[5] R. Dizaji, A.M. Ponsford, "System and Method for Spectral Generation in Radar: U.S. Patent Application 60/365,163," March 19, 2002.

[6] R. Dizaji, A.M. Ponsford, R. McKerracher, "Co-channel Interference Reduction using Adaptive Array Processing: U.S. Patent Application 60/365,152," March 19, 2002.

[7] Z. Ding, K. Hickey, "A multiple hypotheses tracker for a multiple sensor integrated maritime surveillance system," *Proceedings of the 2nd International Conference on Information Fusion,* San Jose, July 6-8, 1999.